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Northern Adriatic Sea hydrographic conditions from October 2002 – September 2003, including the climatic heating anomaly of summer 2003

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CTD data were collected during 38 cruises in the northeastern Adriatic from October 2002 to September 2003 and were analyzed in the context of long-term variability (from data collected over a period of 38 years). A prognostic statistical model was created to fit the long-term data and predicted values were compared to those of the in situ *CTD measurements. As with air temperatures, values attained by the sea in summer 2003 far exceeded those expected by predictive models and were induced by very large heat input from the atmosphere. In conditions of very low regional freshwater input and intrusions of more saline water masses from the south, salinity values in the spring/summer period lay far outside typical salinity values for the area.*

Key words: northern Adriatic, climate, anomaly, statistics, model, temperature, salinity

INTRODUCTION

The northern Adriatic Sea, as a shallow and semi-enclosed sea with high freshwater input, and a wind regime strongly influenced by mountainous regions on its east coast, is a dynamic region with specific atmosphere-ocean coupling characteristics (e. g. CUSHMAN-ROISIN *et al*., 2001). The northern Adriatic gains heat from March to August and water during almost the entire year across the air-sea interface (SUPIĆ & ORLIĆ, 1999). Precipitation, land and river runoff (dominated by the Po River) greatly exceeds water loss due to evaporation (RAICICH, 1996). Seasonal and year-to-year changes of surface temperature and salinity in the region are generally related to air-sea surface fluxes and to the Po River discharge rates, while the corresponding changes of these parameters in bottom layers occur primarily by vertical mixing (SUPIĆ & IVANČIĆ, 2002).

During the wintertime, when the water column is well mixed, freshened Po-influenced waters are generally confined to the western coast, but spread over larger areas of the northern Adriatic during spring and summer seasons when the water column becomes stratified (e.g. FRANCO & MICHELATO, 1991). On average, temperature, salinity and σ_t in the open northern Adriatic (SJ107, Fig.1) ranges from 8-25 °C, 32-38 and 22-29 at the surface and 9-18 °C, about 38 and 28-29 at bottom, respectively (SUPIĆ & VILIBIĆ, 2006). During cold winters dense water (Northern Adriatic Dense Water, NAdDW σ_t~29.5; ZORE-ARMANDA, 1963; ARTEGIANI *et al*., 1997), which subsequently flows southwards (e. g. VILIBIĆ, 2003) along the bottom to the Jabuka Pit, over the Palagruža Sill into the south Adriatic and eventually into the Mediterranean, may form in the area. Warm and high salinity waters (S>38.5) in the central Adriatic ascribed to Modified Levantine Intermediate Water (MLIW; ARTEGIANI *et al*., 1997) may occasionally make a more northerly intrusion as far as Istria (Center for Marine Research, CMR; unpublished data). The general circulation of the Adriatic is cyclonic, consisting of a counterclockwise movement of water northwestward along the Croatian coast (East Adriatic Current, EAC) and a southeastward flow along the Italian coast (West Adriatic Current, WAC; e.g. CUSHMAN-ROISIN *et al*., 2001 (Chapter 3)). In autumn/winter the northern Adriatic is part of the Adriatic-wide cyclonic circulation, with Po River fresh waters generally entrained in the southward flow, close to the western coast (WAC, e.g. ORLIĆ, 1989; KRAJCAR, 2003; 2004). In summer the establishment of cyclonic and anti-cyclonic motions tend to keep the area isolated from the rest of the Adriatic with large quantities of Po waters retained in the area (ORLIĆ, 1989; KRAJCAR, 2003; 2004). However, there is evidence of large interannual variability in northern Adriatic circulation patterns (e.g. SUPIĆ *et al*., 2000). New results indicate that circulation patterns typical for winter may, in some years, also be present in the spring or summer period (GRILLI *et al*., 2005).

The interaction between air and sea has a significant effect on determining local circulation patterns both as a driver of thermohaline circulation and through direct wind forcing (ZORE-ARMANDA & GAČIĆ, 1987; ORLIĆ *et al*., 1994). While both are important components of circulation in the northern Adriatic, thermohaline circulation, induced by spatial variation in density fields, is thought to be the dominant process in the region (e. g. CUSHMAN-ROISIN, 2001 (Chapter 3)). Therefore in conditions of atypical density distribution it is also to be expected that circulation patterns would be atypical.

The summer of 2003 was an exceptional period in which some of the highest temperatures on record were noted across much of western and central Europe (LUTERBACHER, 2004). Even considering long-term warming trends (JONES & MOBERG, 2003), this anomaly was statistically extremely unlikely and may be an indicator of increasingly variable climatic temperatures (SCHAR *et al*., 2004).

During the 2002-2003 period several large projects for collecting marine data were in progress in the Adriatic (e.g. ADRICOSM, DOLCEVITA ADRIA02-03, WISE, ACE, EACE etc.). Considering the unusual climatic conditions during the warm part of 2003, subsequent use of this marine data would benefit from a determination of how typical the data are for the area with respect to climatology.

In this paper we analyse hydrographic data, collected with high temporal resolution in the October 2002-September 2003 interval in the framework of the ADRICOSM project, for the surface and bottom layer with respect to long term statistically modeled data in order to determine if hydrographic conditions in the investigated period were highly atypical. In addition, observed changes in hydrographic parameters were analyzed in the context of air-sea surface fluxes and Po River discharge rates to determine a causal relationship.

MATERIALS AND METHODS

Data collection

Bottle data were collected at stations RV001 and SJ107 off the Istrian coast (Fig. 1) from January 1966 to October 2004 at the surface (0.3 m) and bottom (27±2.5 m at RV001 and 30±2.5 m at SJ107). The frequency of measurements at the two stations in the 1966-1997 interval is given by SUPIĆ *et al.,* (2000). After 1997 the data were collected approximately monthly. Temperatures were measured by protected reversing thermometers (RICHTER & WIESE, Berlin, precision ± 0.01 °C) and salinity was determined to at least ± 0.01 by using a high precision laboratory salinometer. Basic quality check (excluding all data outside three standard deviations) was applied on the data.

CTD data were collected under the framework of ADRICOSM, a pilot program that is part of a project designed to facilitate monitoring, modeling and near real time prediction of coastal current fields in the northern Adriatic Sea coupled with the modeling of river basin and wastewater management, and under Project JADRAN as part of the Croatian national monitoring programme. Data were collected bi-monthly and weekly in the October 2002-September 2003 period using a SeaBird SBE 25 CTD employing a modular configuration, including a SBE 3F temperature sensor and SBE 4C conductivity sensor. Pressure was measured by the SBE 29 temperature compensated strain-gauge pressure sensor. Data were collected with a scan rate of 8 Hz (approx. every 6-7 cm), from

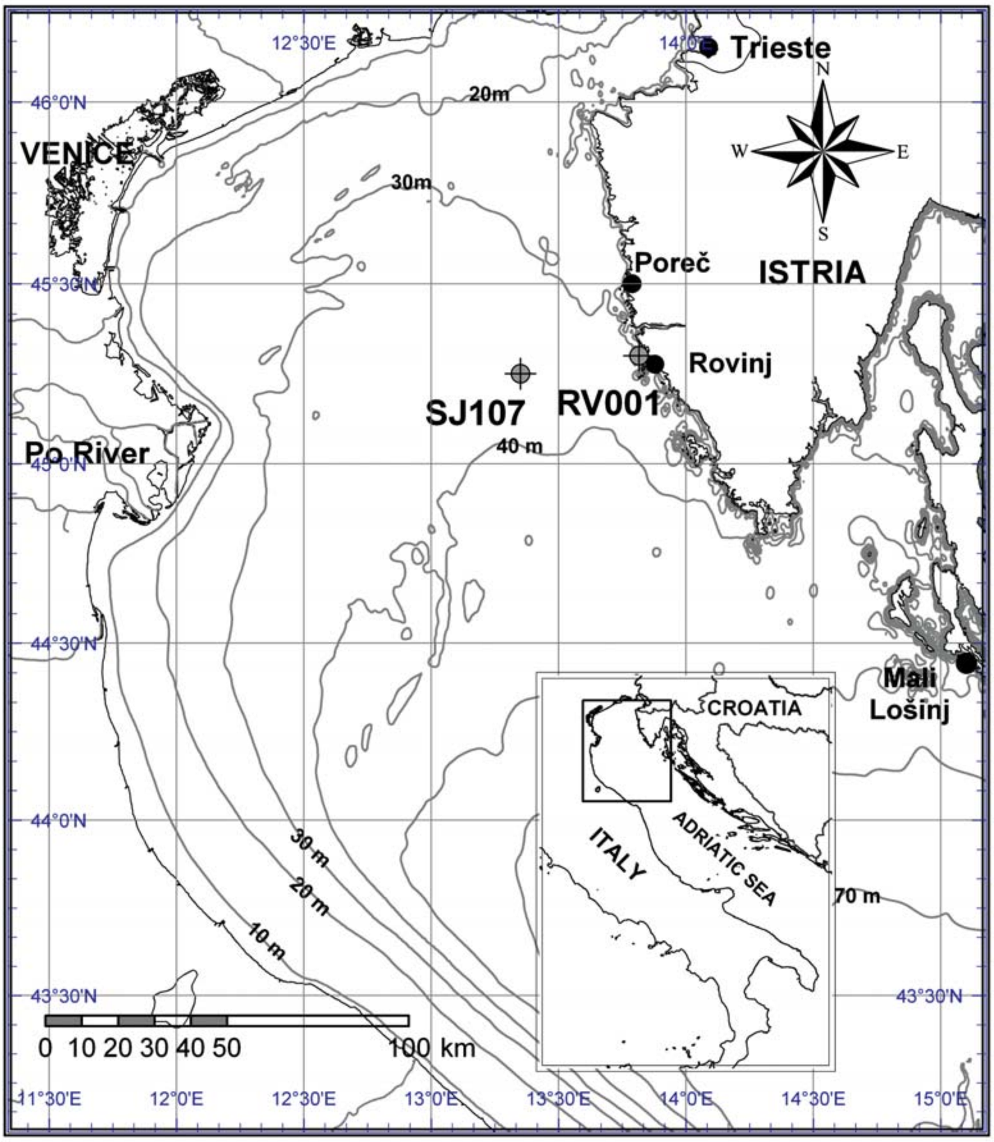

Fig. 1. Map of the northern Adriatic showing the positions of stations SJ107 and RV001

the surface to 2 m above the bottom, grouped into 0.5 m bins and 0.5 m averages were calculated for temperature and salinity. The temperature sensor was calibrated over the range 1.4–32.5 °C (±0.002), conductivity calibrated from 2.8 – 6.1 S m^{-1} (±0.0003) and pressure from ambient to full scale range (±0.1% full scale range).

Statistical model

The long-term temperature and salinity data were used as a basis for creating a model for computing seasonal cycles of temperature and salinity and their respective expected deviations. The statistical model generated from the data was designed to incorporate a mean value and temporal linear trend in addition to yearly and half-yearly harmonics. This model, describing data variability, is of a simple multiple linear regression type and defined by:

$$Y = X\beta + \varepsilon \qquad (1)$$

where Y is an N-dimensional vector of observations with N being the number of observations, X is an N × p matrix of regressors, model formulation β is a p-dimensional vector of parameters and ε is an N-dimensional vector of random disturbances.

For our model we have used β with 6 parameters $p_0 - p_5$ with $X\beta$ defined as:

$$X\beta = p_0 + p_1 * t + \sum_{i=1}^{2} \left[p_{2i} * \cos(w_i * t) + \right.$$
$$\left. + p_{2i+1} * \sin(w_i * t) \right] \qquad (2)$$

where p_i are the parameters, w_i are two frequencies (year and half-year) and t is time. Note that p_0 is the free parameter and p_1 is the regression (trend) coefficient while $\sqrt{[p_2{}^2 + p_3{}^2]}$ and $\sqrt{[p_4{}^2 + p_5{}^2]}$ define yearly and half-yearly amplitudes respectively. The strategy for determining a solution was to find the best fit of data (Y) to model (X) by a least squares method at the 95 % confidence level. In order to quantify the quality of the obtained results we used variance between model and data (var SM) given by:

$$\mathrm{var}\, SM = \frac{1}{12} \sum_{k=1,12} \frac{\sum_{i=1}^{M(k)} (y_{ik} - y_{SM})^2}{M(k) - 1}$$

where $M(k)$ is number of available data for the month k in the 1966-2004 interval, y_{ik} are data observations in k-th month (k=1, ..., 12), and y_{SM} is the model predicted value for the observation time. In the same manner we defined variance between calculated monthly means and data, var MM as:

$$\mathrm{var}\, MM = \frac{1}{12} \sum_{k=1,12} \frac{\sum_{i=1}^{M(k)} (y_{ik} - y_{MM}(k))^2}{M(k) - 1}$$

where $y_{MM}(k)$ is the monthly mean for k-th (k=1, .., 12) month.

In addition monthly mean positive or negative deviations were defined by calculating the mean of all positive or negative differences, respectively, between the model and collected data for a particular month.

Heat and water fluxes

Surface heat and water fluxes for the northern Adriatic have been computed following the procedure described by SUPIĆ & ORLIĆ (1999). Total downward heat flux from the atmosphere to the sea (Q; W m^{-2}) was computed as the sum of the fluxes due to insolation (Q_s), longwave radiation (Q_l), latent (Q_e) and sensible heat flux (Q_c). Q_s was computed by the method proposed by REED (1977) and adapted for use in the Mediterranean area by GILMAN & GARRETT (1994) giving the insolation at a certain location and time as a function of cloud cover. As there are no direct measurements of Q_l, Q_e and Q_c in the northern Adriatic against which formulae may be verified, three different sets of formulae (termed a, b and c) previously utilized in the Mediterranean had been applied to compute Q_l, Q_e and Q_c. The sets were proposed by (a) GILL (1982), (b) BUNKER *et al.* (1982) and (c) GILMAN &

GARRETT (1994) respectively. Q_l, Q_e and Q_c were finally computed as average values obtained from three different estimations. Q_l is proportional to the fourth potential of sea surface (a and c) or air (b) temperature with corrections depending on water vapor pressure and cloud cover (a, b and c), air temperature (c) or air and sea temperature (b). Latent and sensible heat fluxes are induced by heat transfer by evaporation and conduction, respectively. They are proportional to wind speed and to differences between the observed specific humidity and the saturation humidity at the sea surface temperature (Q_e; the humidities are computed from air and water vapor pressure) and to the difference between air and sea temperature (Q_c). In addition, the two parameters depend on semi-empirical coefficients which are, in the case of b and c, estimations computed from wind speed and air and sea temperature differences. Downward water flux (W; mm d^{-1}) was computed as the difference between precipitation (P) and evaporation [$E = - Q_e/(L\rho_0)$], assuming that water density ρ_0 and latent heat of evaporation L have constant values of 1000 kg m^{-3} and $2.5X10^6$ J kg^{-1}, respectively. The fluxes at three locations in the area (Trieste, Rovinj and Mali Lošinj) have been calculated from monthly means of standard meteorological data (air pressure, air temperature, scalar wind speed, cloud cover, specific humidity and precipitation) and SST data. The data were provided by Trieste University, Hydrometeorological Institute, Zagreb, and the Maritime Meteorological Center, Split. As the air pressure was not measured at Rovinj, data collected at the nearby station Poreč (45° 13' N; 13° 36' E) were used in the analysis. Monthly means of meteorological data (except precipitation which had been measured daily) were computed from hourly values at Trieste and from measurements taken three times a day (6, 13 and 20 h UTC) at Rovinj and Mali Lošinj. The monthly means of SST for Trieste have been derived from daily (8 h UTC) collected data. Monthly means of SST for St. Ivan lighthouse [45° 03' N; 13° 37' E; T_s (IV)] near Rovinj and for Mali Lošinj were computed from monthly means of measurements taken three times a day (6, 13 and 20 h UTC). Monthly means of SST for Rovinj [T_s (RV)] were computed using the regression formula: $T_s(RV)=1.09*T_s(IV)-0.6$. The formula was derived from monthly means of simultaneous measurements of SST at Rovinj and St. Ivan Island in the 1984-86 and 1988-92 periods, with correlation coefficients of 0.99 between both data sets.

The surface fluxes computed for the northern Adriatic in the 1998-2001 interval as described above (SUPIĆ & VILIBIĆ, 2006) shows an overall qualitatively good agreement with surface fluxes computed on the basis of operational data sets for the entire Adriatic by CHIGGIATO *et al*. (2005). This lends confidence to the quality of the method used in the estimation of fluxes but also indicates that month-to-month changes in Adriatic surface fluxes are relatively uniform. This latter assumption is also supported by the fact that correlation coefficients between 204 monthly values of Q at stations in Rovinj and Mali Lošinj in the 1966-1992 interval were very high – 0.93 (significant at the 99 % level) – in spite of the fact that seasonal differences in surface fluxes between the two stations are very much pronounced (up to 60 W m^{-2}; SUPIĆ & VILIBIĆ, 2006).

Po River discharge rates

Using a similar spectral analysis method to that used for temperature and salinity, average annual flow rates, and mean positive and negative deviations, were determined for Po River flow rates for the 1917-2004 period.

RESULTS

Surface fluxes

Average monthly values of surface air and water fluxes computed for the 1966-1992 interval, shown in comparison with the October 2002-September 2003 data in Fig. 2 and Fig. 3, are discussed in more detail elsewhere (SUPIĆ & ORLIĆ, 1999).

Downward heat flux from the atmosphere to the sea during the October 2002-September 2003 period showed significant deviations from

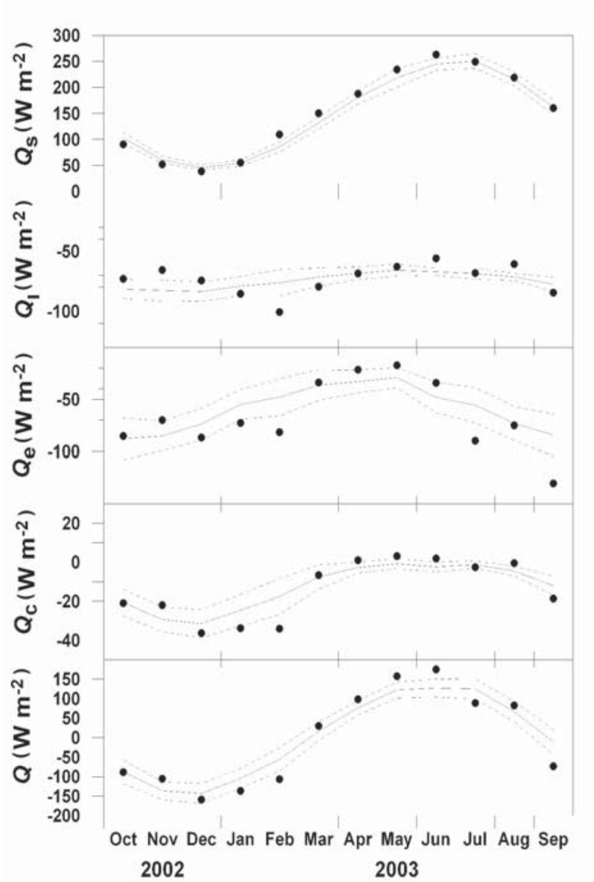

Fig. 2. Average monthly values (solid lines) and standard deviations (dashed lines) of surface heat fluxes due to insolation (Q_s), longwave radiation (Q_l), evaporation (Q_e), conduction (Q_c) and total heat flux (Q) calculated for the northern Adriatic from 1966-1992. Values computed for the October 2002-September 2003 period are shown as circles

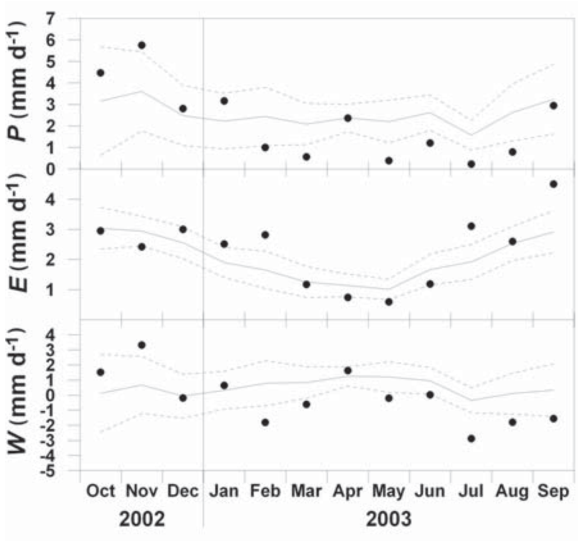

Fig. 3. Average monthly values (solid lines) of precipitation (P), evaporation (E) and total air-sea water flux (W) with their respective standard deviations (dashed lines), calculated for the northern Adriatic from 1966-1992 data. Data for the October 2002-September 2003 period are shown as circles

the long-term mean with lower than anticipated heat gain by the sea in January-February, July and September and higher than expected in November and from April to June (Fig. 2). Significant deviations are defined as anomalies greater than 1 standard deviation in absolute value.

Low heat loss in November was mostly due to reduced heat loss by longwave radiation that occurred in conditions of high air and sea temperatures and low cloud cover (Fig. 4). The intense heat loss at the start of 2003 was primarily due to very large heat losses induced by longwave radiation and latent and sensible heat flux. The longwave radiation was especially intense in February when both cloud cover and water vapor pressure were significantly lower than average. The latent and sensible heat losses were outside the standard deviation range during the entire January-February interval, when differences between air and sea temperature were much higher than average and wind was very strong. However, significantly higher heat transfer to the sea than normal was noted from April to June. In this period the sea gained more heat than in the same interval in any of the years between 1966 and 2000. This excess heating was primarily due to high insolation and small negative latent and sensible heat fluxes (Fig. 2). During this period values for the three fluxes lay outside their respective calculated standard deviations. While excessive insolation was due to low cloud cover during that three month period, heat loss by the sea, as reflected by negative values for latent and sensible heat, was lower than usual in conditions of moderate winds and where sea surface temperatures were lower than air temperatures. The unusually low surface heat gain in July was due to high evaporation that occurred with average monthly air and sea temperatures and wind strength being close to average values (within the range

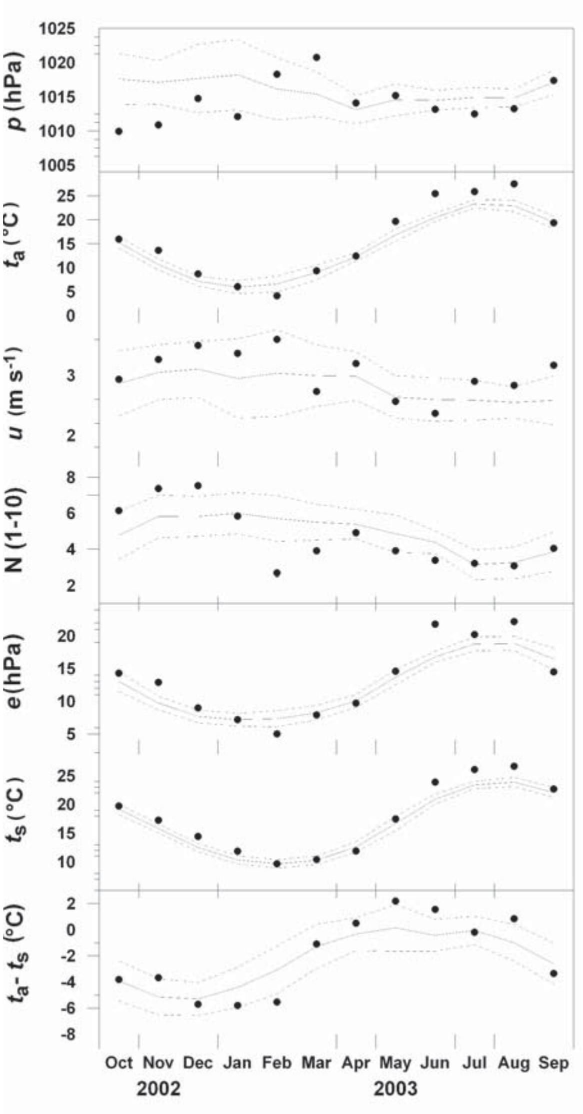

Fig. 4. Average monthly values (solid lines) of air pressure (p), air temperature (t_a), wind speed (u), cloud cover (N), water vapor pressure (e), seawater temperature (t_s) and difference between air and sea surface temperature (t_a-t_s) with their respective standard deviations (dashed lines), calculated for the northern Adriatic from 1966-1992. Data from October 2002-September 2003 are shown as circles

of standard deviation). This high evaporation was presumably induced by a strong bora wind episode (CMR, unpublished data).

In September high heat loss, induced by longwave radiation, evaporation and conduction, also reduced sea surface temperatures to average values. In this month wind was also much stronger than average and the associated vertical mixing also acted to reduce sea surface temperature. Water vapor pressure was exceptionally low although differences between air and sea temperatures were much smaller than average.

Indeed, during most part of the investigated period the values of the air-sea water flux were lower than average (in December, February-March, May-September; Fig. 3). Extremely negative values coincided with intervals in which precipitation rates were especially low (in February-March and in May-August) or were induced by very high evaporation rates in conditions of very strong wind (September). The sea gained a large amount of water in November 2002 when precipitation was significantly above average.

Po River Annual discharge cycle

Modeled flow rates for the River Po show yearly maxima in November and at the end of May with the lowest discharge rate found in August (Fig. 5). While the mean negative deviation from the average remains relatively constant throughout the year, the mean positive deviation is large during the autumn and spring periods. During the October 2002-September 2003 period, Po River discharge rates were significantly higher than average from mid-November to mid-January and thereafter decreased to significantly lower than average values until the end of the investigated period.

Model

Our model for the description of changes of temperature and salinity in the 1966-2004 interval consists of a yearly cycle described by two harmonics integrated with a linear trend (as shown, for example, in Fig. 6 for temperature in the surface layer at RV001). The coefficients for fundamental model parameters at stations RV001 and SJ107 are given in Tables 1 and 2. The model was found to explain a high degree of variance in the 1966-2004 interval for the surface (95-96 %) and bottom (75-88 %) temperatures at both stations. However, the degree of variance in salinity explained by the model for the same period was much lower - 31-35 % at the surface

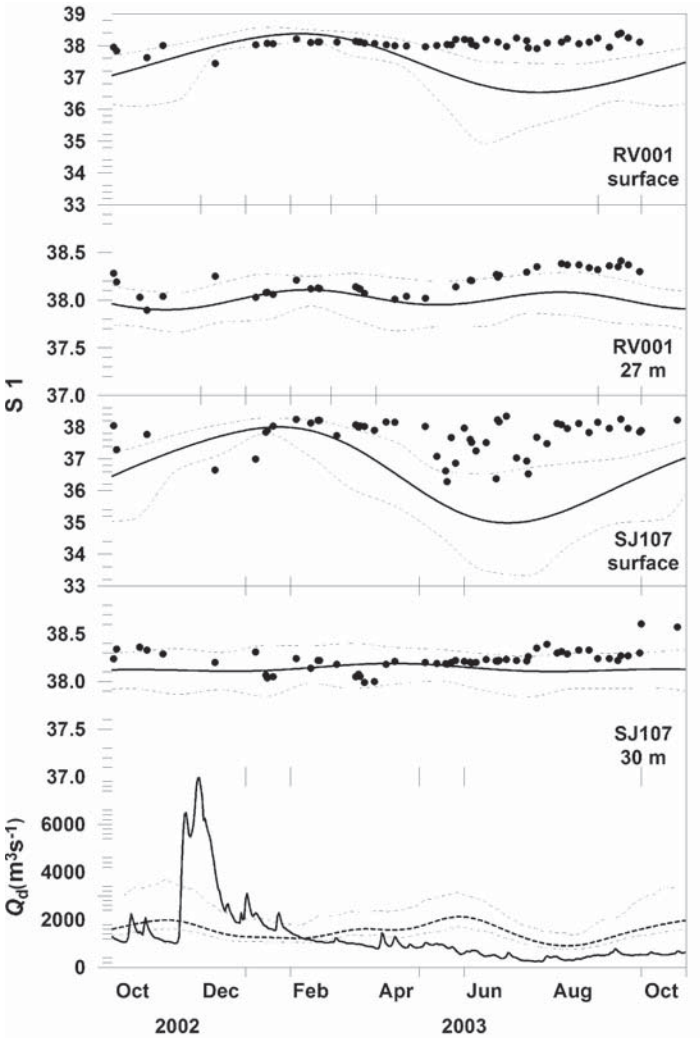

Fig. 5. Modeled surface and bottom salinities derived from long-term bottle data series (solid line) with average positive and negative deviations from the model (dotted line). Circles indicate data (bottle and CTD) collected during the 2002-2003 period. Po River flow rates for the 2002-2003 interval (solid line), including average long-term flow rate (heavy dashed line) with mean positive and negative deviations (thin dashed lines)

and only 5-9 % at the bottom. Previous studies of annual variability of temperature and salinity in the region were mostly based on the standard and widely used method of desribing annual cycles of a certain parameter by considering 12 monthly means (e. g. SUPIĆ & IVANČIĆ, 2002). However, variances between our model and the original long-term data (Var *SM*) were in all cases lower (for surface and bottom temperature at RV001, surface temperature at SJ107, surface salinity at RV001), equal (bottom salinity at RV001 and SJ107) or just slightly higher (bottom temperature ar SJ107 and surface salinity at SJ107) than the variability between monthly means computed from the same set of long-term data and the data (Var *MM*). That suggests that our model is typically as good as - or better than - the widely accepted representation of the annual cycle based on monthly means, even for salinty in spite of the fact that variance explained by our model for salinity is low.

Positive linear trends were obtained for all parameters at both stations. However, for the 38 year period, the temperature trend at both

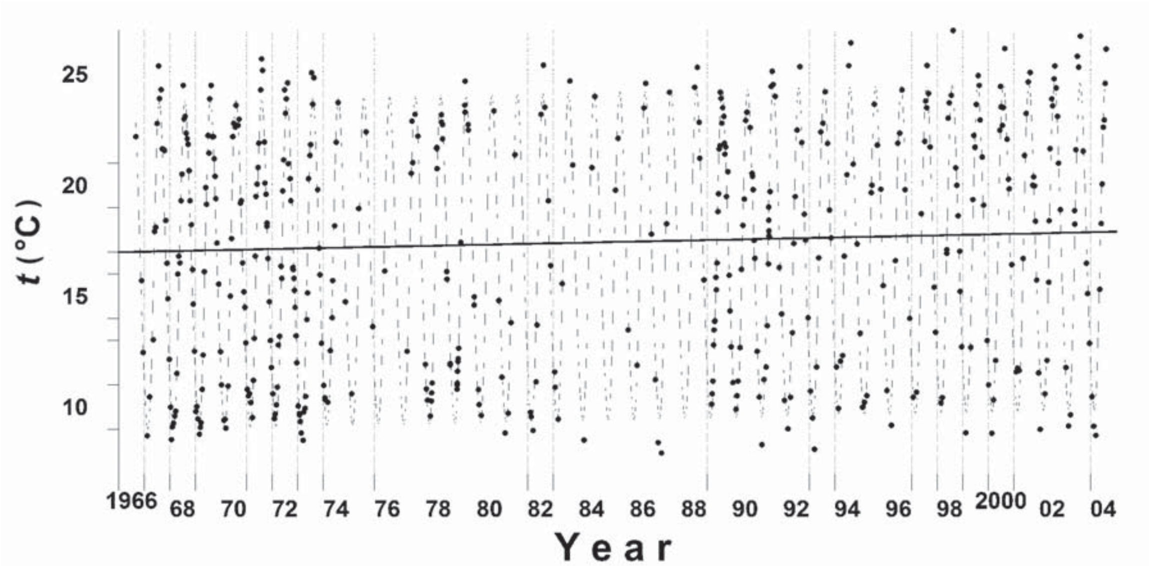

Fig. 6. Surface temperature data and model fit, comprising of two harmonics and linear trend, for station RV001 in the 1966-2004 interval

Table 1. Mean values (t), regression (trend) coefficients (r_t), amplitudes (A_y – yearly, A_{hy} – half yearly, A_d – daily) and correlation coefficients (r^2) for temperature at depth (z) at stations RV001 and SJ107. Variance of the model from long-term data (VarSM) and variance of monthly means from long-term data (VarMM) are also given

Station	*z* (m)	*t* (°C)	r_t (°C year^{-1})	A_y (°C)	A_{hy} (°C)	r^2	VarSM (°C^2)	VarMM (°C^2)
RV001	0.3	16.98	0.02	7.27	0.73	0.96	1.05	1.56
	27.0	14.42	0.02	4.33	0.79	0.88	1.24	1.26
SJ107	0.3	18.25	0.03	7.75	0.92	0.95	1.67	2.23
	30.0	13.38	0.01	3.61	0.95	0.75	2.00	1.99

Table 2. Mean values (S), regression (trend) coefficients (r_S), amplitudes (A_y – yearly, A_{hy} – half yearly, A_d – daily) and correlation coefficients (r^2) for salinity at depth (z) at stations RV001 and SJ107. Variance of the model from long-term data (VarSM) and variance of monthly means from long-term data (VarMM) are also given

Station	z (m)	S	r_S (year^{-1})	A_y	A_{hy}	r^2	VarSM	VarMM
RV001	0.3	37.04	0.017	0.92	0.07	0.31	0.89	0.91
	27.0	37.90	0.006	0.03	0.08	0.09	0.08	0.08
SJ107	0.3	36.23	0.004	1.47	0.18	0.35	1.90	1.88
	30.0	38.06	0.005	0.03	0.02	0.05	0.07	0.07

stations was more pronounced in the surface (0.8-1.1 °C for that period) than in the bottom layer (0.4-0.8 °C). For salinity, while similar slight positive trends were noted for the surface and bottom layers at SJ107 and the bottom layer at RV001, a much stronger positive trend was found for the surface layer at RV001 (0.6 over 38 years). In previous work, SUPIĆ *et al.* (2004) computed yearly means for sea temperature, salinity and density in the 1921-2000 interval in the surface and bottom layers at RV001 and found no trends. However, data only from years when sampling was performed during at least 10 separate months were considered.

Therefore many data were excluded from the analysis. However, by pre-empting data gaps with sinusoidal functions our method made it possible to use all the data.

Generally, caution must be used when analyzing trend values in the absence of systematically collected and higher density data. STRAVISI (2000) has found that systematically collected daily sea surface temperatures in the northern Adriatic (Trieste) for the 1946-1999 period suggested a trend of 0.3 °C (for that period). While that trend and the temperature trends in this work are not directly comparable due to different geographical locations and different data time series, the positive trend found by STRAVISI (2000) increases confidence that the positive trend found here is qualitatively correct. Such a positive trend is consistent with other work, for example, BARALE *et al*. (2005) determined a 2 °C positive trend in sea surface temperature for the entire Adriatic for the 1981-1999 period on the basis of satellite data. Trends in salinity found in this work also suggest an increase of 0.2-0.6 over the 38 year period and may be related to more persistent intrusions of high salinity water from the middle Adriatic (RUSSO *et al*., 2005) along with changing patterns of riverine input (especially from the River Po) over the past four decades (PRECALI, 1995). Also, the weaker positive trend at the offshore station (SJ107) may be due to that station being under greater influence from Po River freshwaters than station RV001 that lies further eastwards. Such salinity trends may be compared to previous work showing long-term salinity increases in various parts of the Adriatic for different time periods (ZORE-ARMANDA *et al.,* 1991; PAINTER & TSIMPLIS, 2003). However, as no systematic salinity data are available for this area it is impossible to compare and validate our salinity data with respect to long-term trends. This is also important as the statistical model does not describe to a sufficiently high degree yearly salinity variations for trend values found here to be viewed with confidence.

Model annual cycle of temperature and salinity

The annual cycle of surface temperatures, as given by our model (Fig. 7) at stations RV001 and SJ107, follow a well defined path, ranging from a winter temperature minimum in late February (around 10°C at both stations) to a summer maximum at the beginning of August (around 25 °C at RV001 and slightly higher at SJ107). In bottom layers minimum temperatures (about 9.5 °C at both stations) occurred earlier at RV001 (second part of February) than at SJ107 (begining of March). The bottom maximum temperature also occurred earlier at RV001 (in September, about 18 °C) than at SJ107 (in October, about 17 °C). The water column is relatively well mixed and temperatures generally uniform from November to February. From March, the surface increases in temperature more quickly than the bottom layer, coinciding with the downward air-sea heat flux becoming positive (Fig. 2). By the end August, the surface layer begins to cool while the temperature of the bottom layer continues to rise. This is related to the period when air-sea heat flux becomes negative, resulting in cooling of the surface, and increased vertical mixing increases the temperature of the bottom layer. Spatial differences do not seem important in the November-February period as surface temperatures at SJ107 and RV001, as well as bottom temperatures, are very similar. From March to August, the surface layer at offshore SJ107 increases in temperature more rapidly than at near-shore RV001 and remains warmer until October. Small scale variability in surface heat fluxes may play a role, although such variations are not captured by our surface flux calculations. However, the advection of low salinity waters from the River Po in the surface layer is more pronounced at SJ107 than at RV001 (e.g. Fig. 7) and increases the stratification degree and reduces the transfer of heat to bottom layers. In the botton layer temperatures at RV001 increase more quickly than at SJ107 and also remain higher until October.

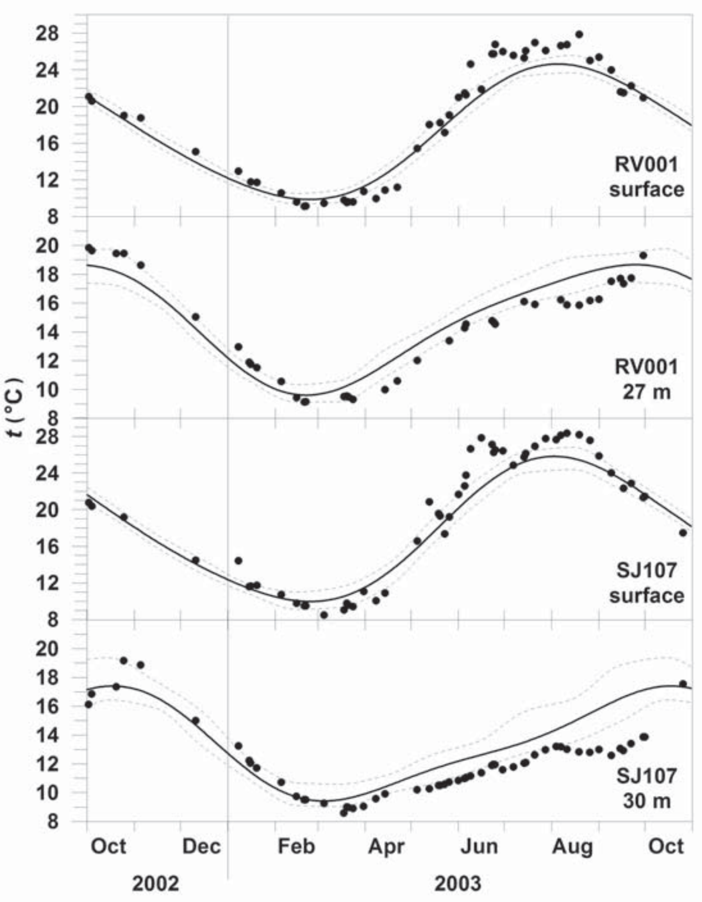

Fig. 7. Modeled surface and bottom temperatures derived from long-term bottle data series (solid line) at stations SJ107 and RV001. Average positive and negative deviations of data from the model are shown by the dotted line. Data (bottle and CTD) collected during the 2002-2003 period shown by circles

In fact, thermal changes in the surface layer can generally be related to changes in surface heat flux with sea surface maximum and minimum temperatures being attained after the periods of maximum and minimum downward heat flux (heat flux maximum from May-July and mimimum from November-January; Fig. 2).

Model surface salinity values at the two stations show qualitative similarities, with maximum salinity values occuring in January (SJ107, about 38.0) or February (RV001, about 38.4) and minimum values at the end of June/beginning of July (SJ107, about 35) or in mid-July (RV001, about 36.5). Salinity values do not show a strong seasonal cycle as in the bottom layer of SJ107 it is almost constant (about 38.1) while the bottom layer at RV001 shows greater variability (up to 38.1 in February and August and down to about 37.9 in November). For the surface layer, higher salinity values dominate during the cold part of the year while a reduction in salinity is noted for the warmer summer period. This effect is related to River Po freshwaters which, while normally directed south along the Italian coast, spreads eastwards over the northern Adriatic in stratified conditions in spring-summer. Po-derived freshwater presence is generally more pronounced at SJ107 than at RV001 and its presence is noted earlier. Air-sea water flux remains relatively constant throughout the year (Fig. 3) and is not significantly responsible for the pronounced annual salinity cycle (Fig. 5).

While salinity in the surface layer is always lower offshore at SJ107 than near-shore at RV001, bottom salinity values show the opposite behavior where salinity is always higher at SJ107 than at RV001. For the surface layer, SJ107 is closer to the Po River delta and salinity values are more affected there by riverine input than at RV001. On the contrary, due to the more pronounced stratification degree at SJ107, vertical mixing is disfavored and higher salinity water persists in the bottom layer.

While uniform water column temperatures are noted from November to February, surface and bottom salinity values are similar only for short periods of time - at SJ107 salinity values are similar only in January, though not the same, while at RV001 salinity is uniform throughout the water column at the beginning of December and April. In these periods, because of vertical mixing, changes in surface salinty due to the air-sea water flux and riverine input are also reflected in bottom salinity values. At station RV001, the autumn period before December shows a slight decrease in bottom salinity with a concomittant rise in salinity at the surface related to vertical mixing. However, the second yearly bottom salinity minimum at RV001 in May, coinciding with a strong salinity decrease in the surface layer, may be related to convection or vertical mixing in conditions of lower stratification degree. On the contrary, bottom salinity values offshore at SJ107 are nearly constant, suggesting that the stronger stratification degree at this station results in weaker vertical mixing in the water column.

Temperature and salinity, October 2002-September 2003

Temperature data, at the surface and bottom, collected from October 2002 to September 2003, generally followed (within one standard deviation) model values in the cold part of the year (Fig. 7). To February, all temperatures were slightly higher, and from February to the end of April slightly lower, than modeled values. The most significant divergence from the predicted model values for a sustained period was noted for the surface layer in the warm part of the year from May to August. Two maxima were noted in June and August and separated by a short-lived period of lower temperatures in July that corresponded with an episode of strong bora (i.e. northeasterly) wind (CMR, unpublished data). The sea surface temperature maxima were found to exceed those predicted by up to 3°C and lay far outside the average predicted deviation for that time of year. On the contrary, bottom temperatures from May to August at both stations were constantly lower than, and generally lay outside one standard deviation of, statistically modeled values (Fig. 7). In September 2003, while temperatures at the surface at both stations and at the bottom of station RV001 were very similar to modeled values, bottom temperatures at station SJ107 deviated even further from expected values.

Average heat loss in October, and much less heat loss in November, may be responsible for higher sea surface and bottom temperatures at the end of 2002 and January 2003. The greater heat loss during January and February may have induced a reduction in temperature in both the surface and bottom layer from February and which was observed until April in the surface layer and much longer (to September) in the bottom layer

However, significantly higher heat transfer to the sea than normal was noted from April to June and accounts well for the extremely high sea surface temperatures of summer 2003. The unusually low surface heat gain in July resulted in a lower sea surface temperature in that month. In August, air-sea heat flux was above the expected value, again inducing warming of the sea surface. Heat loss was more intense in September than expected from average values, resulting in a rapid decrease in sea surface temperature. Due to the strong heating of the surface layer from April and the resulting stratification of the water column, bottom temperatures remained significantly lower than expected until September 2003.

Data collected from October to December 2002 show that salinity values were higher than modeled values except for the surface layer in December when salinity decreased. Salinity values in the surface layer at SJ107 and RV001 were similar to expected values (within one standard deviation) until the end of March and April, respectively, and then remained significantly higher than modeled values until the end of the investigated period. For the bottom layer, salinity was noted to remain close to expected values until mid-July and the start of June at SJ107 and RV001, respectively. After this, salinity generally increased and typically varied from model values by one standard deviation or more.

Despite a positive (downward) air-sea water flux from October to November 2002, surface salinity values were higher than modeled values and may be related to the advection of more saline water from the south. While this occured in conditions of low Po River flow rates, the input of Po waters at the end of 2002 resulted in reduction in surface salinity which was more pronounced at the offshore station (SJ107). In January, Po River flow rates and water flux were close to average values and salinity values were similar to those modeled values. However, from February, both water flux and riverine input were typically below average values resulting in surface salinity values remaining significantly higher than expected until September 2003. Advection of more saline water from the south might be additionally respondible for salinity values being much higher than usual.

Salinity data for the bottom layer at RV001 and SJ107 lay consistently close to the modeled values until June and July, respectively (Fig. 5). The higher than expected salinity values thereafter is likely related to the intrusion of higher salinity waters from the middle Adriatic.

DISCUSSION AND CONCLUSIONS

Variations in sea temperature and salinity at a near-shore and an offshore station in the northeastern Adriatic, based on all available data covering the period 1966-2004, were described by a model using a combination of two harmonics and a linear trend. The method was found to describe a high precentage of the variance in thermal changes, although not in salinity changes. However, the model approach typically proved to be as good as, and often better than, the widely used method of analysis of annual cycles based on the computation of monthly means.

Unlike land-based meteorological stations that may continuously monitor atmospheric parameters, good coverage of marine data is oftentimes limited by the number of cruises available in a given period. Due to this temporal non-unformity, trends in marine data are difficult to determine. Therefore, spectral analysis, as used in this work, is a useful method for pre-empting gaps in the data set. Results showed a positive trend in thermal changes over the 38 year period, and is consistent with previous studies on systematically collected data. However, trends obtained for salinity may be artefacts as variance described for salinity is low and there are no systematically (e.g. daily) collected data in the region, in which salinity variations are very pronounced on both spatial and temporal scales, against which we can compare our results. In addition, more sophisticated models that include additional variables such as, for example, Po River discharge rates or Mediterranean Oscillation Index (which influences high salinity water advection; GRBEC *et al*., 1998; SUPIĆ *et al*., 2004) are required to better model long-term changes and trends in the local salinity parameter.

Trends in temperature and salinity in the northern Adriatic are significant as they would be expected to impact on the important dense water formation processes in the area. For example, a positive trend in temperature would disfavor dense water formation, while a positive trend in salinity might help compensate for rising temperatures. Indeed, long-term trends also have extremely important consequences for seasonal and interannual thermohaline circulation patterns at the Adriatic sub-basin level (ARTEGIANI *et al*., 1989) with subsequent effects at the Mediterranean basin (REID, 1979) and global scales (BETHOUX *et al*., 1999).

Deviations from the statistically modeled annual temperature and salinity cycles have been described for the October 2002-September

2003 interval. In some periods of that interval, temperature and salinity lay far outside expected values based on long-term modeled values. Temperature and salinity conditions during the winter months favored dense water formation in the area, based on salinity values which were typically the same as, or higher than, average values while temeratures in the water column were significantly lower than usual. During the summer period, very high salinity values were noted in the area, suggesting that waters from the middle Adriatic, possibly of Mediterranean origin, had intruded into the northern Adriatic. In addition, Po River discharge rates were very low and the usual spring freshwater pulse was absent. Sea surface temperatures were very high during the period of anomalously high atmospheric temperatures experienced in summer 2003.

This result indicates that during much of the October 2002-September 2003 period hydrographic conditions were unusual. As circulation is generally of thermohaline origin, and bearing in mind the large year-to-year variability observed in the region, circulation patterns reported for the 2002-2003 period, based on a large quantity of data collected within the frameworks of various projects (ORLIĆ *et al*., 2003; LYONS *et al*., in press), might not be typical.

Changes in long-term statistically modeled annual cycles of temperature and salinity at the two stations have been explained qualitatively by changes in average annual cycles of surface fluxes and Po River rates. Differences in annual cycles between stations were ascribed to the surface layer at the offshore station being more influenced than the near-shore station by waters of River Po origin. Deviations in hydrographic conditions, in the October 2002-September 2003 period, from the statistically modeled annual cycle were subsequently explained by deviations in surface fluxes and Po rates from average values. These results have prepared the ground for future investigations of changes in hydrographic conditions in the water column based on numerical modeling.

In conclusion, this work has highlighted the exceptionality of the October 2002- September 2003 period as high positive air-sea heat flux during the warm part of the year, coupled with low precipitation and reduced riverine freshwater input, resulted in anomalously high surface temperatures and salinities and cautions using data from 2003 as representative of the area without sufficient qualification.

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Hidrografska svojstva sjevernog Jadrana od listopada 2002. do rujna 2003. godine, u razdoblju s anomalno toplim ljetom

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SAŽETAK

Analizirani su podaci o temperaturi, salinitetu i gustoći skupljani na 38 krstarenja u sjeveroistočnom Jadranu od listopada 2002. do rujna 2003. godine i uspoređeni s prognoziranim vrijednostima iz statističkog modela. Model je načinjen na temelju podataka sakupljanih u ovom području u tridesetosmogodišnjem razdoblju. Površinske su temperature mora ljeti 2003. godine bile daleko iznad očekivanih, što je bila posljedica pojačanih površinskih protoka topline iz atmosfere u more. U proljeće i ljeto 2003. godine vrijednosti saliniteta bile su također značajno iznad prosjeka, zbog niskih dotoka slatke vode i intruzije slane vode iz srednjeg Jadrana.

Ključne riječi: sjeverni Jadran, klima, anomalija, statistika, model, temperatura, salinitet